A Sharp-to-continuous Interface Tracking Transition Algorithm for Multicomponent Fluid Flow Simulation

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The volume tracking method [1], also known as volume-of-fluid (VOF) method with interface reconstruction, is a broadly used numerical method that simulates immiscible multicomponent fluid flow where the interface is represented as a sharp boundary and is evolved as part of the solution of the flow equations. In volume tracking, the underlying mesh is fixed (Eulerian framework) and the interface is not explicitly tracked as in the front-tracking approach—it is captured by the material volume fraction and is geometrically reconstructed by piecewise linear interface planes (PLIC) [1]. Geometric reconstruction allows accurate estimation of mass and momentum fluxes and avoids numerical diffusion of the interface. The method's main drawback is when the interface reconstruction becomes under-resolved, i.e., when the interface length scale becomes smaller than three to four grid points. Interface reconstruction is known to introduce numerical surface tension, which breaks a filament into a series of droplets whenever the filament is under-resolved [1]. Adaptive mesh refinement can help avoid under-resolution, but a fully developed flow will still generate filaments that cannot be resolved without enormous computational cost. The goal here is to propose a complementary new approach that consists of transitioning locally from volume tracking to a continuous interface representation (i.e., without interface reconstruction) in regions where volume tracking has become erroneous.

In order to locally identify the regions where the interface reconstruction has become erroneous, we base the switch criterion of the transition algorithm on the interface curvature information. A good indication that the mesh size is too coarse to resolve the interface length scale is when the interface curvature is becoming too large with respect to the underlying mesh size. To compute interface curvatures, we employ the height function method, a very efficient and accurate technique [2]. For the sharp representation of the interface we employ the volume tracking method of Rider and Kothe [1]. For the continuous interface representation we employ the interface preserver approach of Dendy and Rider [3], also known as the artificial steepening or compressive limiter method, in which the volume fraction gradients are steepened in order to keep the numerical diffusion to a minimum. Our algorithm is the following: at every time step, we compute the interface curvatures. Based on the interface curvature value, we then assign the interface treatment flag either to volume tracking or interface preserver. The advection fluxes at the cell faces are then estimated based on the flow velocity direction and the interface treatment flag (volume tracking or interface preserver). Finally, the volume fractions are updated in time.

To illustrate the transition algorithm potential, we present the test case of a single vortex deformation flow field, a common test case used for testing material advection algorithms. Initially a circular interface of radius 0.15 is located at (0.5, 0.75) in a unit square domain, and a vortex velocity field is specified on the entire domain as a function of time. We run our simulation until T/2—the time at which the maximum stretching occurs on a 32 x 32 mesh (a coarse mesh to highlight the benefit of a transition algorithm). The volume fraction contours are shown in Fig. 1 at time $t = 2$. Note that for the volume tracking method the interface planes are not plotted, but the volume fraction contours are plotted to facilitate the comparison with the interface preserver and transition algorithm methods. We observe that on the 32 x 32 mesh the (1) volume tracking algorithm leads to the breaking of the interface into droplets, (2) interface preserver method slightly diffuses the interface but keeps the correct interface topology, and (3) transition algorithm avoids the interface break-up. In order to quantify our results, we define a global error metric δ as a function of time to measure the advection error on the coarse mesh with respect to a reference solution on a fine mesh (512 *x* 512). The error δ is plotted in Fig. 2. This plot shows that the overall accuracy is greatly improved by using our material interface transition algorithm based on a curvature switch criterion. Additional numerical test cases of complex deformation flow field and Rayleigh-Taylor instability are given in [4].

A new algorithm has been designed to transition locally from volume tracking to interface capturing within a single fluid field Eulerian formulation. The transition criterion of the algorithm is based on interface curvature, a geometric measure. This algorithm has the potential to lead to a more accurate prediction of surface areas, which is very valuable when modeling coupled multiphysics phenomena.

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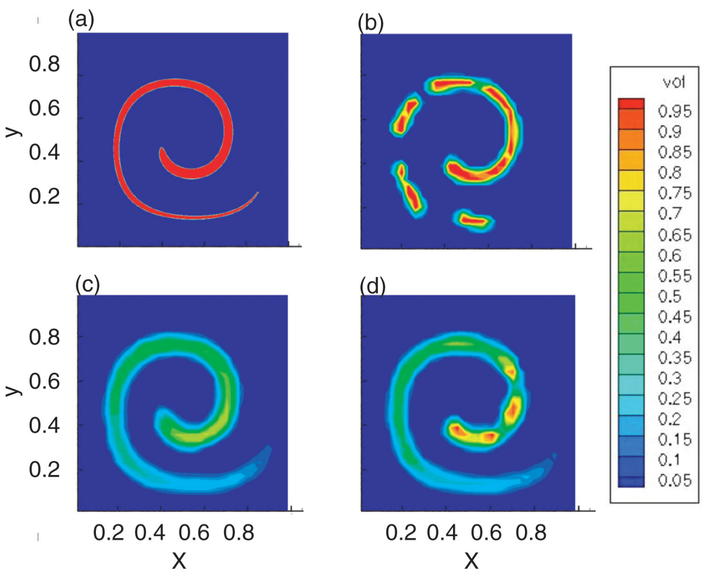

Fig. 1. Volume fraction contours at time t = 2 for the single vortex deformation flow field of period T = 8 on a 32 x 32 mesh. (a) Reference volume tracking solution on a 512 x 512 mesh, (b) volume tracking, (c) interface preserver, and (d) transition algorithm.

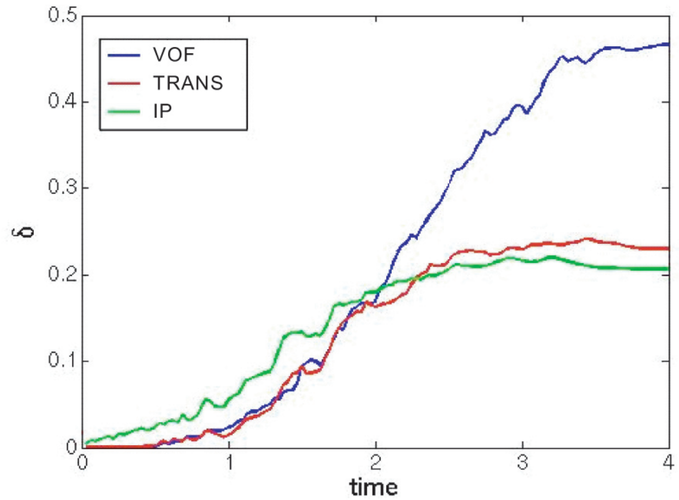

Fig. 2. Volume fraction error versus time for the single vortex deformation flow field on a 32 x 32 mesh.

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